National Transportation Safety Board

Office of Research and Engineering

Washington, DC 20594

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VIDEO STUDY

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A. ACCIDENT

Location: Joplin, Montana
Date: September 25, 2021
Time: 3:56 PM local time
Vehicle: Amtrak train 7 (Empire Builder)

B. SUMMARY

B.1. The accident

On September 25, 2021, about 3:56 p.m. local time, westbound National Railroad Passenger Corporation (Amtrak) train 7 (also known as the Empire Builder) carrying 154 people derailed in a right-hand curve at milepost 1014.57 on the BNSF Railway (BNSF) Hi Line Subdivision near Joplin, Montana. As a result of the derailment, three passengers died and 44 passengers and crew were transported to local hospitals with injuries. Damage was estimated by Amtrak to be over $22 million.

Amtrak train 7 consisted of two locomotives and 10 railcars. Eight of the 10 railcars derailed with four railcars derailing on their sides. In the vicinity of the accident area, BNSF authorizes train movements with a traffic control system. Train movements are coordinated by a BNSF train dispatcher located at the Dispatch Center in Fort Worth, Texas. Train movements on the Hi Line Subdivision are governed by operating rules, special instructions, timetable instructions, and the signal indications of the traffic control system and supplemented with an overlaid positive train control (PTC) system. The maximum allowable speed on this section of track was 79 mph for passenger trains.

B.2. Objective and Scope of the *Video Study*

The objective of this Video Study was estimating the lateral deviation of the right and the left rails, the length of the misaligned track section, and the vertical rail deflection of the right rail (as seen from a westbound train) preceding the location where rail cars derailed.

B.3. Summary of results

It was found that there were significant lateral rail deviations as well as a significant vertical rail deflection.

C. DETAILS OF THE INVESTIGATION

C.1. Estimation of lateral rail deviations

A camera mounted on the windshield of the lead locomotive of Amtrak train 7 recorded video that showed lateral deviations of rails ahead of the train. Figure 1 shows one frame from that video. This and other frames from the video were used to estimate the maximum lateral deviations of the rails from their original locations.

The video was recorded by a March Networks video system. It had 702x240 resolution that the March Networks DVR Player stretches vertically to generate 702x480 video for viewing and for video frame extraction. The video frame in Figure 1 is in the 702x480 format. The frame rate of the video was 15 frames/second.

The estimation of the maximum deviations of the right and the left rails from their original locations in the area seen in Figure 1 was based on fitting polynomial curves to the rails in the video frames.

The rail profile at the derailment location was AREMA 132RE with 3.00" rail head width, 6.00" rail base width and 7.12" rail height. Since the sun was located left of the track, Figure 1 shows the shadows of the rails to the right of the rails. The most visible lateral locations on the rails were the boundaries between the rail heads and the shadows, i.e., the right edges of the rail heads. These edges were considered to be the locations of the rails in the analysis that follows.

The rail deflections had to be measured relative to properly aligned rails that served as a reference. The rails used as a reference were on the same curved section of the track and located 175 feet before the location of the lateral deviations. Figure 2 shows a zoomed section of the reference track with a 3rd order polynomial curve fitted to the right edge of the right rail head. The red dots are the points used for deriving the polynomial fit and the yellow curve is the polynomial fit.

The same process was then used to fit a 5th order polynomial curve to the misaligned right rail seen in Figure 1. The higher order of the polynomial fit was required because the misaligned rail had a more complex shape than the reference rail. The fit is shown in Figure 3.

The video frame with the reference rail and the fitted polynomial curve was then placed on top of the video frame with the misaligned rail and its fitted polynomial curve. The reference video frame was assigned 50% transparency so that both tracks and both polynomial curves were visible. Figure 4 shows the image of the zoomed superimposed video frames. The yellow curve is the fit to the reference rail that is based on the red data points. The red curve is the fit to the misaligned right rail that is based on the yellow data points. The maximum deviation of the misaligned right rail relative to its reference shape is marked as Dright in the figure.

The same process was repeated for the left rail. Figure 5 shows the image of the zoomed superimposed video frames. The yellow curve is the fit to the reference rail that is based on the red data points. The red curve is the fit to the misaligned left rail that is based on the yellow data points. The maximum deviation of the misaligned left rail relative to its reference shape is marked as Dleft in the figure.

The deviations Dright and Dleft were measured in a computer program based on images zoomed more than those in Figure 4 and Figure 5. The lateral resolution of the video frames, 702 pixels, was relatively low. It resulted in each video frame pixel width corresponding to 1.4 inches at the location where the maximum rail deviations were located in Figure 4 and in Figure 5. The width of the pixels was large relative to the rail deviations that were being estimated. Consequently, minimizing the effect of the wide pixels on the accuracy of the rail deviation estimates was a challenge that had to be dealt with, as described next.

The rail deviation estimation process outlined above was performed several times for both the right and the left rails. Additionally, the rail deviations were also estimated by overlaying video frames without using the fitted polynomial curves. All the estimated maximum lateral deviations were in the range between 2.6 inches and 3.2 inches.

When evaluating the accuracy of the estimated maximum deviations, the relatively low resolution of the video that resulted in each pixel at the misaligned track location being 1.4 inches wide must be considered. The most conservative accuracy assumption is that the distance between the reference rail and the misaligned rail can only be measured in multiples of the pixel width, resulting in maximum error being one pixel width. Since the horizontal pixel width is 1.4 inches, this leads to maximum misalignment estimates of between 2.6±1.4 inches and 3.2±1.4 inches, or, when combined, 2.9±1.7 inches.

However, it is estimated that the actual maximum measurement errors are lower that the ±1.4 inches that are based on the above most conservative assumption. Two facts lead to this lower-error assumption. First, the fitted polynomial curves had resolution higher than the 1.4 inch resolution of the images. The bent rail had to have continuous shape rather than a jagged-edge shape that would result from limiting the rail shape to passing only through the centers of the video pixels. It is estimated that the fitted polynomial curves that were allowed to pass smoothly anywhere through the video pixels reduced the maximum possible error due to the 1.4 inch pixel width.

Additionally, each vertical pixel in Figure 1 represents about 20 inches of rail length at the location of maximum rail deviation. Figure 4 shows that the deviation is near its maximum value along about 20 feet of track. These 20 feet of track correspond to about $20 \times 12/20 = 12$ pixels heights (i.e., the vertical dimensions of the pixels) in Figure 4. If the lateral distance between the reference rail and the misaligned rail was being measured along only one horizontal line of pixels, the error could be as large as ±1.4 inches. However, analysis shows that the distance between the reference rail and the misaligned rail is about the same along all 12 horizontal lines of pixels where the deviation was near maximum. It is unlikely that all 12 lines of pixels would involve measurement errors as large as +1.4 inches or as large as -1.4 inches. Therefore, it is concluded that the maximum measurement error is smaller than ±1.4 inches.

The two reasons why the rail deviation estimation error is smaller than the maximum ±1.4 inches were explained above. Therefore, an estimate that is more realistic than the most conservative estimate is that the maximum rail deviations are between 2.6±0.7 inches and 3.2±0.7 inches, or, when combined, 2.9±1.0 inches.

The length of the misaligned track area was estimated using a mathematical model of the optics of the camera. The model was capable of superimposing onto video frames lines perpendicular to the rails and located at specific distances from the locomotive and from each other. The model was calibrated using rails, rail ties, buildings and equipment seen in the video when the locomotive was approaching the 1st Avenue crossing located about 1.9 miles east of the derailment location.

Figure 6 shows a zoomed detail from the video frame in Figure 1 with superimposed green lines spaced by 20 feet from each other. The figure shows that the track section that was significantly misaligned to the right from its original location is about 40 feet long. If even minor rail misalignments are considered, the misaligned section was about 60 feet long. If it is assumed that the misalignment follows a curve consistent with a theoretical buckling model, the shape of the 60-foot misaligned rail segment can be approximated by a cosine wave.

More specifically, if the maximum estimated misalignment is D=2.9 inches and the length of the misaligned area is L=60 feet, the misalignment d(x) at location x feet along the 60 feet rail segment can be approximated by

$$d(x) = D/2 \times (1-\cos(360° \times (x/L))) \qquad \text{where } 0 \le x \le L \tag{1}$$

Figure 7 is a plot of the rail misalignment as specified in Equation (1) for L=60 feet and D=2.9 inches. As can be appreciated from Figure 6, the video does not have the resolution that would allow accurate measurement of the misalignment along the 60-feet-long rail segment. Figure 7 is the assumed theoretical shape of a 60-feet-long buckled beam with clamped ends when the deflection in its center is 2.9 inches. This shape can be used as an approximation of the actual shape in dynamic simulations of rail vehicles moving across the misaligned track section in this accident.

Videos were available from seven other locomotive cameras on trains that passed the Amtrak train 7 derailment location before Amtrak train 7 and did not derail. Three cameras were on Amtrak trains and four cameras were on BNSF trains. Table 1 lists data on Amtrak train 7 and the seven additional trains. The table shows that in addition to Amtrak train 7, only the BNSF7380 train video showed measurable lateral rail deviations. It passed the derailment location about two hours and fourteen minutes before Amtrak train 7. The rail deviation size estimated based on the BNSF7380 train video was the same as that estimated based on the Amtrak train 7 video, 2.9±1.0 inches.

The videos from the other six trains that passed the derailment location earlier did not show measurable lateral rail deviations. Rail deviations of 1 inch or less are not measurable, given the uncertainty in the method of analyzing the videos. Figure 8 shows the track segment with the measurable lateral rail deviations in the Amtrak train 7 video. Figure 9 shows the same track area in the Amtrak train 135 video where the deviations are not measurable. Figure 10 shows the track segment with the measurable lateral rail deviations in the BNSF7380 train video. Figure 11 shows the same track area in the BNSF4182 train video where the deviations are not measurable. The BNSF4182 train passed that location 12 minutes before the BNSF7380 train.

Table 1. List of trains that passed the location where Amtrak train 7 derailed

Train	Date	Time	Direction	Speed (mph)	Measurable rail deviation	Roll detected?
Amtrak 207	9/24/2022	1:00 PM	east	80 (assumed)	no	yes
BNSF5184	9/24/2022	1:30 PM	east	40 (assumed)	no	yes
Amtrak 135	9/24/2022	3:50 PM	west	79	no	yes
BNSF5286	9/25/2022	11:40 AM	west	39	no	yes
Amtrak 8	9/25/2022	12:37 PM	east	81.5	no	yes
BNSF4182	9/25/2022	1:30 PM	east	61	no	yes
BNSF7380	9/25/2022	1:42 PM	east	48	yes	yes
Amtrak 7	9/25/2022	3:56 PM	west	78.4	yes	yes

C.2. Estimation of vertical rail deflection

It was observed in all eight videos from the trains listed in Table 1 that the locomotive front ends, where the cameras were mounted on the windshields, underwent a significant roll transient when passing the location where the lateral rail deviations were measurable in the videos from Amtrak train 7 and from the BNSF7380 train. Figure 12 shows the measurement of the roll angle of the camera of Amtrak train 7 at a location where the roll with respect to horizon was at its local positive maximum of 4.2°. Positive roll angle on westbound trains indicates that the right rail was lower than the left rail.

The goal of the analysis was detecting local vertical clearances that resulted in vertical rail deflections when wheelsets passed over them. When only one of the two rails develops a local vertical clearance, it is expected that the locomotive and the camera attached to its windshield will develop a short-duration roll angle transient. This roll transient should not be confused with the roll angle due to superelevation that is present over a longer track segment, or with the roll of the locomotive body with respect to the trucks caused by inertial forces on a curve, or with the roll misalignment of the camera with respect to the locomotive. The short-duration roll transients caused by local vertical rail clearances are in addition to superelevation, in addition to roll due to inertial forces on a curve, and in addition to camera installation misalignment, as explained next.

Figure 13 is a plot of the measured Amtrak train 7 camera roll angle. The figure shows a roll transient lasting about 3.15 seconds between about time 0.85 seconds (point A), when the transient started, and time 4 seconds (point F) when the transient was over. During the 0.6 seconds marked in the figure, the roll angle increased by about 2.4° and reached a local maximum value of 4.2°. It is estimated that the 69 feet that the train traveled during this period is related to the length of the deflected rail segment, possibly being half of it, or all of it, or a fraction between half and all of it.

Assuming a rail gauge of 56.5 inches, a locomotive roll angle increase by 2.4° is caused by the right rail deflecting vertically by $56.5 \times \tan(2.4°) = 2.4$ inches. It is estimated that in the absence of the vertical rail clearance and the absence of the transient it caused, the roll curve section showing the transient in Figure 13 would have looked like the hypothetical roll represented by the dotted green line.

If the response to the vertical rail clearance was static, the roll response would have ended at about point C, where the vertical clearance ended, and the roll angle curve would have looked like the black broken-line curve in the figure. But it was not so. Point B is at the maximum positive (right-side-down) roll angle of 4.2°. At about time 2.1 seconds, the roll angle peaked at a left-side-down roll angle of about -0.9° and at time 3 seconds it again peaked at a right-side-down roll angle of about 1.4°.

The three local peaks of the locomotive roll response point to a dynamic response where the locomotive roll, yaw and lateral motions were coupled with the lateral and yaw motions of the trucks and the wheelsets. This resulted in a dynamic transient that lasted beyond the section of the vertical rail clearance. The coupling between the locomotive body motions and the motions of the locomotive wheelsets probably resulted in lateral wheel flange to rail impacts. When Amtrak train 7 was at the derailment location, the lateral rail deviations were already present. It is estimated that all the cars in the train experienced transients caused by the vertical clearance that were similar to the locomotive transient.

Table 1 indicates that the measurable lateral rail deviation appeared after the BNSF4182 train passed the vertical deflection area. Figure 19 shows the roll angle of BNSF4182. Points B and D marked in Figure 19 are the first two peaks of the transient roll response. They are analogous to points B and D of Amtrak train 7 in Figure 13, but their polarity is reversed because Amtrak train 7 was moving west and BNSF4182 was moving east. The presence of peak D in Figure 19 indicates that the locomotive of BNSF4182 experienced a dynamic transient similar to the dynamic transient that the Amtrak train 7 locomotive experienced. This opens the possibility that the lateral wheel flange to rail impacts of the BNSF4182 locomotive and rail cars contributed to the development of the measurable lateral deviation of the rails that appeared after BNSF4182 passed the location of the vertical clearance.

Figures 13 through 20 show the measured roll angles of the cameras on all eight analyzed trains. Figure 13 shows the roll angle for the derailed train Amtrak 7, but Figures 14 through 20 are arranged to show the other trains from the earliest at the derailment location to the latest. Note that there are westbound trains, such as Amtrak train 7, and there also are eastbound trains. The first peaks of roll transients of the eastbound trains are negative because for them the deflecting rail is the left one. The westbound trains entered the curve from the east and the eastbound trains entered it from the west. Therefore, there are some differences between the westbound train and the eastbound train roll transient in addition to the polarity of peaks.

The BNSF trains were moving at about 40 mph while the Amtrak trains were moving at about 80 mph. Therefore, there also are some differences between the Amtrak and BNSF roll transients caused by the speed differences. However, all eight train videos show an initial fast roll magnitude increase in the 2° to 3° range, pointing to a local vertical rail deflection in the 2 inches to 3 inches range. In all the cases, the response to the vertical clearance was a dynamic transient that involved motions of the locomotive body as well as of the trucks and wheelsets and it lasted longer than the time to travel across the vertical deflection area.

C.3. Discussion of estimated lateral rail deviations and vertical rail deflection

The above sections detected and estimated lateral rail deviations and a vertical rail deflection based on videos recorded by locomotive cameras. Both the lateral rail deviations and the vertical rail deflection were at a location preceding the location where rail cars derailed. Analysis was based on videos recorded with cameras on eight train locomotives. The eight analyzed trains are listed in Table 1. The earliest of the eight trains, Amtrak train 207, passed the derailment location about 27 hours before Amtrak train 7, the train that derailed.

Analysis of the available eight train videos revealed that the latest two videos, from BNSF7830 and Amtrak train 7, showed measurable lateral rail deviations of both rails. The magnitude of the deviations was estimated as 2.9±1.0 inches. The six earlier train videos did not show measurable deviations. Therefore, it is possible that the measurable lateral deviations developed when or after train BNSF4182 passed the accident location.

Analysis of the eight train videos indicated that there was a vertical clearance at the accident location that caused a roll to the right of the westbound trains and a roll to the left of the eastbound trains. The roll was estimated based on the orientation of the horizon as seen in video frames. Since the cameras were installed on the locomotives, the estimated angles were those of the locomotives when the rails were supporting the load carried by the front trucks of the locomotives. The estimated vertical clearance under the right rail (as seen from a westbound train) was in the 2 inch to 3 inch range. The earliest train video evaluated that showed the clearance was from Amtrak train 207, which passed the accident location about 27 hours before the train that derailed. There is no video-based information on the presence of the vertical clearance before the time when Amtrak train 207 was at that location.

The roll response of the eight trains to the vertical clearance indicated that it was a dynamic response rather than a static response. A static response would have generated a locomotive roll response proportional to the vertical rail clearance. The locomotive roll response would have ended at the track location where the clearance ended. However, the estimated roll angles indicated a dynamic transient response where the initial roll to the right (using the westbound Amtrak train 7, Figure 13, as an example) was followed by a roll to the left and then was followed by another roll to the right 2.15 seconds after the transient started. The total duration of the transient (point A to point F) was about three times the length of time it took the train to travel the length of the track segment with the vertical rail clearance (point A to point C).

It is estimated that during these dynamic transients excited by the vertical clearance, wheels on the locomotives and the rail cars could have been impacting the rails. Published studies have shown that rails with initial lateral misalignments buckle at temperatures lower than rails that are not misaligned. This is the reason why rails that buckle tend to deflect outward on curved track. The rails in this accident deflected inward. A possible reason for inward deflection is that the degree of the curve on which Amtrak train 7 derailed was only 1.55° so that the initial outward deviation of the curved rails from being straight was very small. It is possible that train wheels that impacted the rails in the inward direction caused dynamic misalignment in the inward direction that was larger than the small initial outward deviation of the curved rails.

D. CONCLUSIONS

Video captured by a locomotive camera was used to estimate the maximum lateral deviation of the right and the left rails and the length of the misaligned track section preceding a location where rail cars derailed. It was estimated that the maximum lateral deviations of the rails were 2.9±1.0 inches, the length of the track where the lateral rail deviations were significant was about 40 feet, and the total length of the misaligned track section was about 60 feet.

Videos from cameras on eight locomotives were used to estimate vertical rail deflections caused by vertical rail clearance at the location where the lateral rail deviations were detected. It was estimated that the locomotives caused vertical rail deflections in the 2 inches to 3 inches range.

The response of the locomotives to the vertical rail clearance was dynamic and could have caused significant lateral wheel-rail impact forces that contributed to the development of the lateral rail deviations.

FIGURES

Figure 1. Frame from Amtrak train 7 video that shows the misaligned rails

Figure 2. Polynomial fit to the right rail that Is used for reference

Figure 3. Polynomial fit to the misaligned right rail

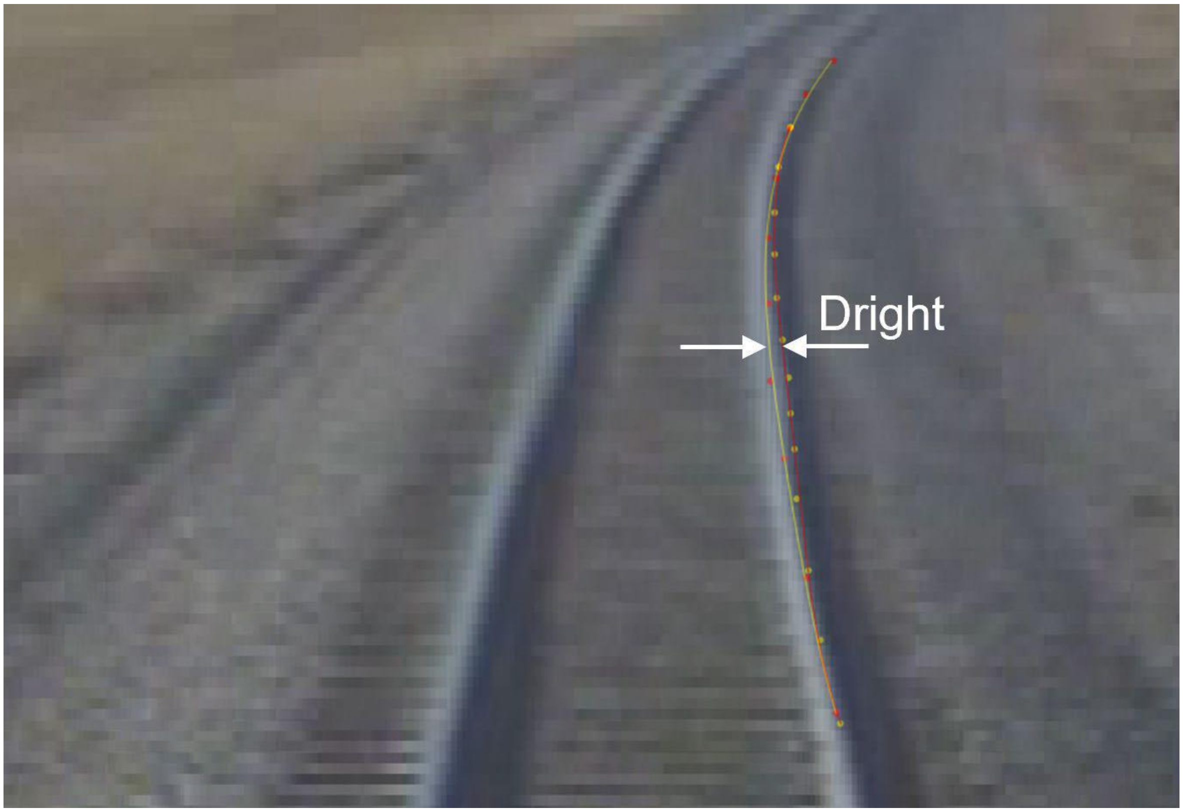

Figure 4. Measurement of the right rail misalignment

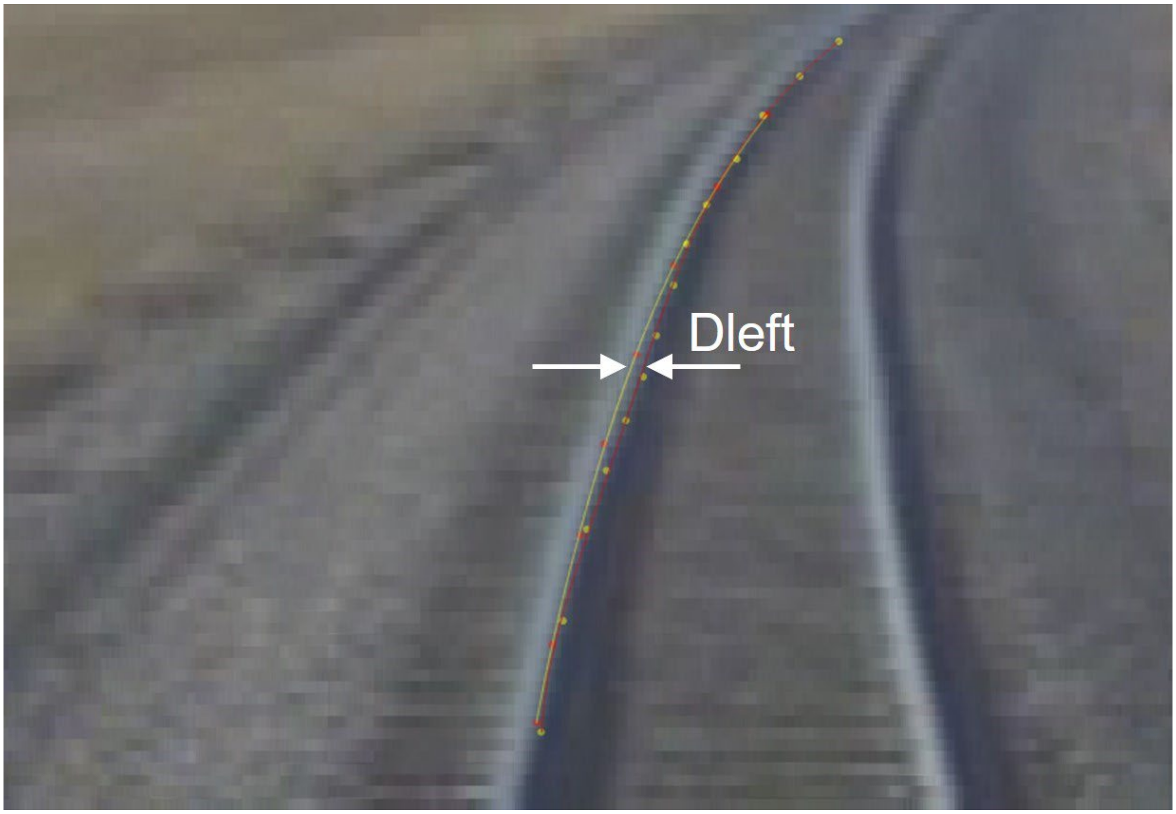

Figure 5. Measurement of the left rail misalignment

Figure 6. Misaligned track section with markers spaced by 20 feet

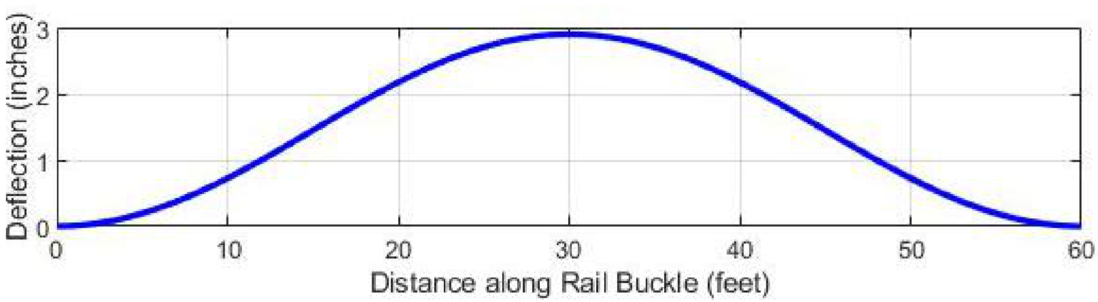

Figure 7. Theoretical shape of a misaligned rail section

Figure 8. Rail misalignment location – Amtrak train 7 video

Figure 9. Rail misalignment location – Amtrak train 135 video

Figure 10. Rail misalignment location – BNSF7380 train video

Figure 11. Rail misalignment location – BNSF4182 train video

Figure 12. Measurement of camera roll with respect to horizon

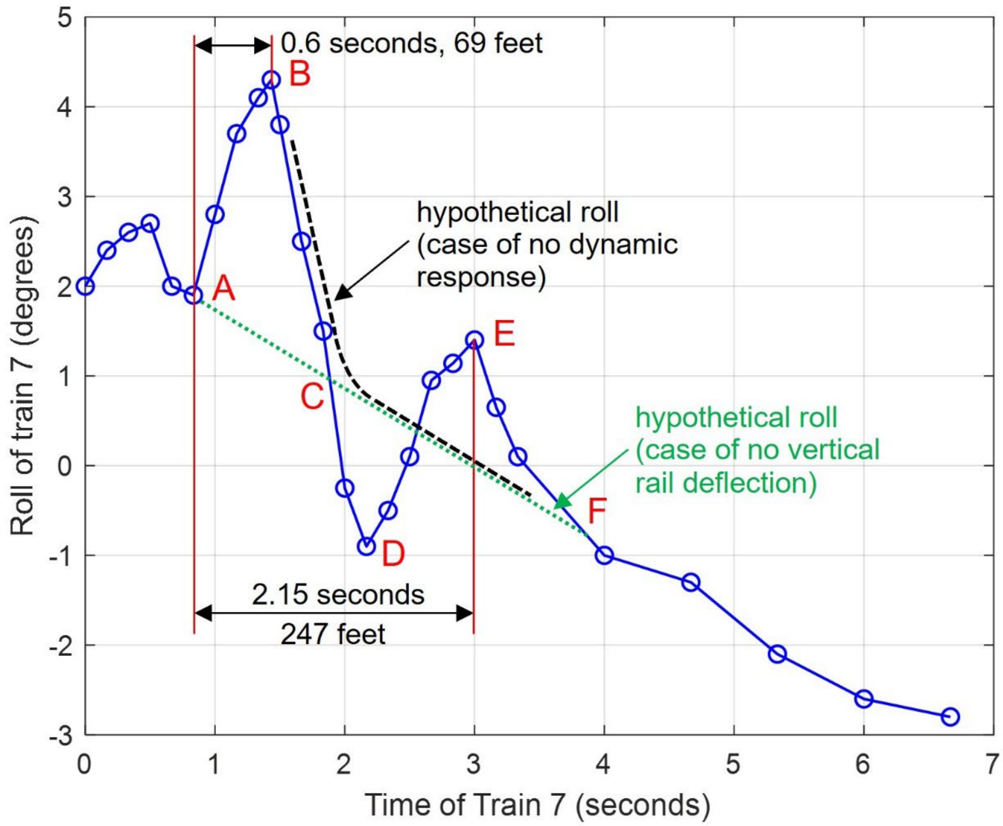

Figure 13. Measured roll angle of Amtrak train 7 (westbound)

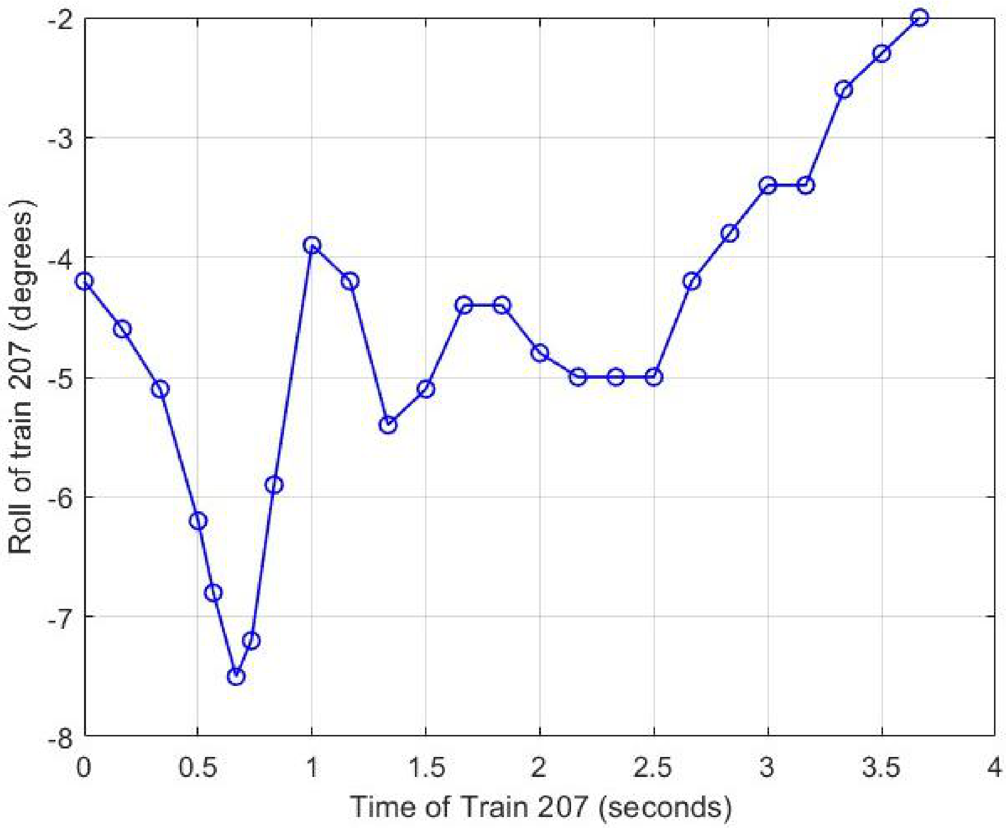

Figure 14. Measured roll angle of Amtrak train 207 (eastbound)

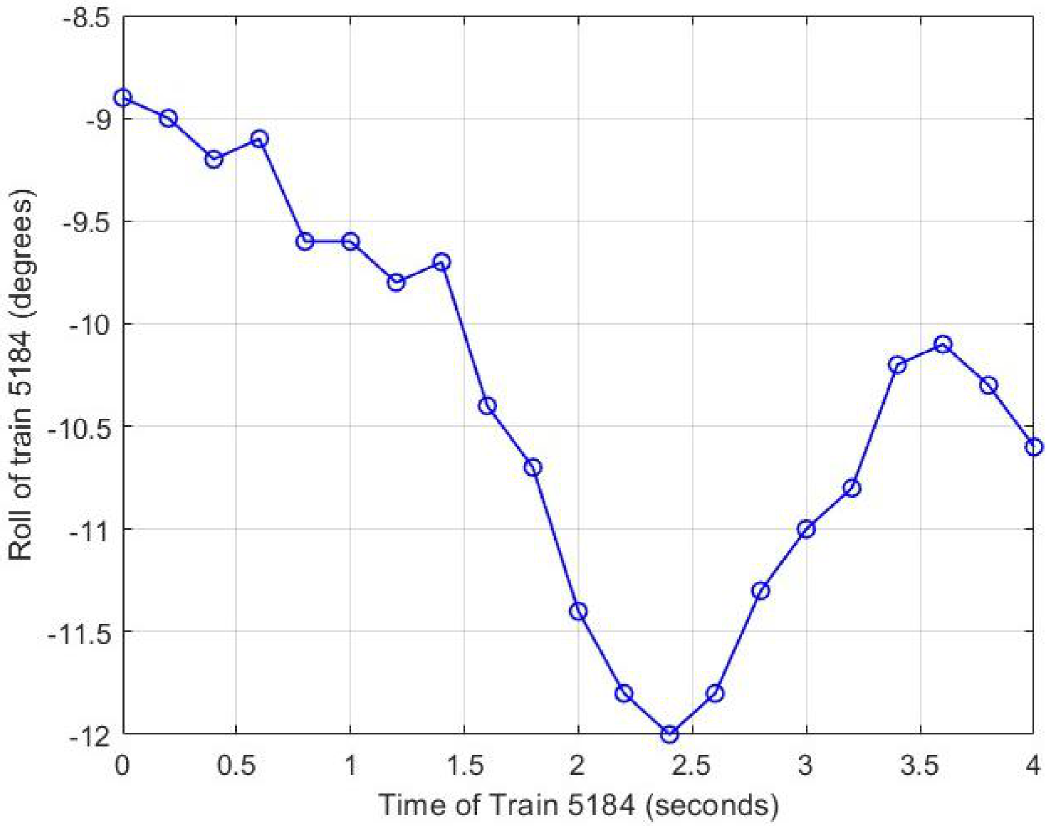

Figure 15. Measured roll angle of BNSF5184 train (eastbound)

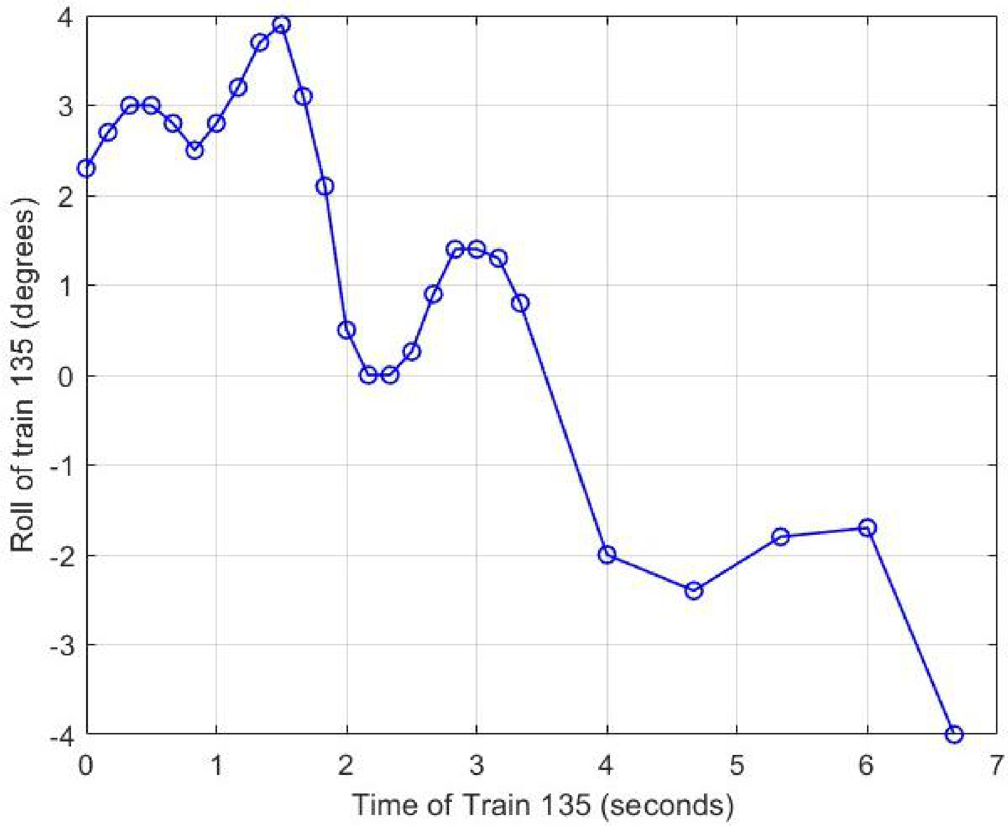

Figure 16. Measured roll angle of Amtrak train 135 (westbound)

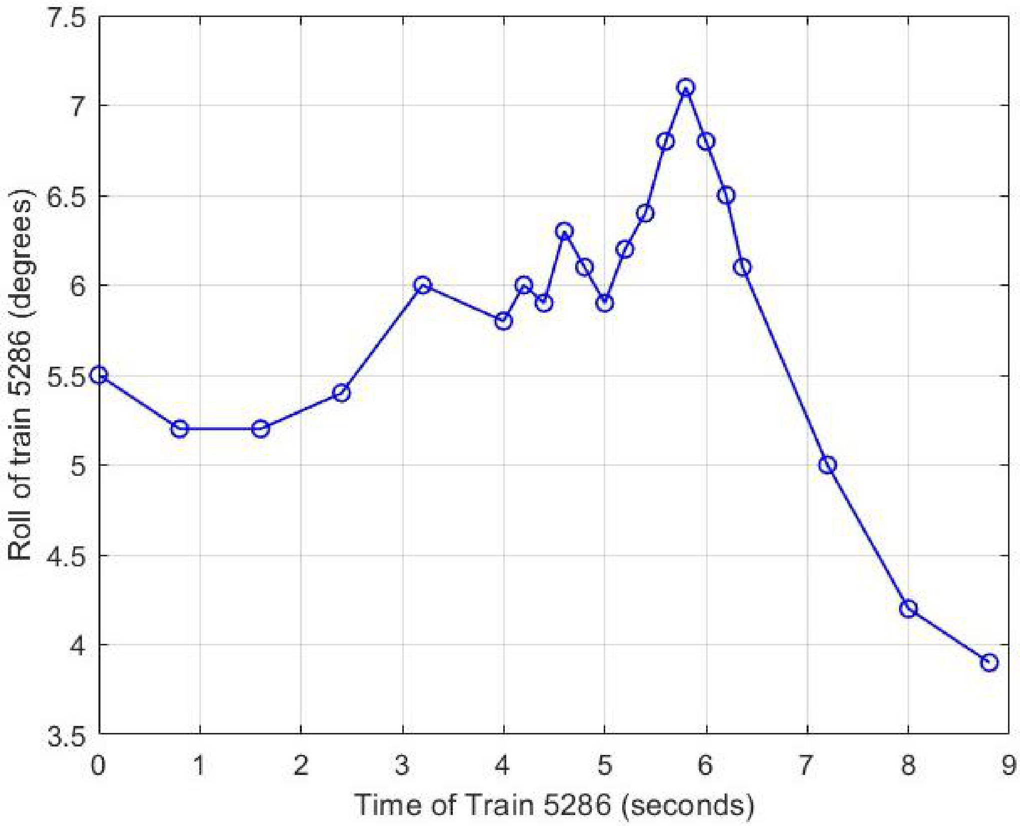

Figure 17. Measured roll angle of BNSF5286 train (westbound)

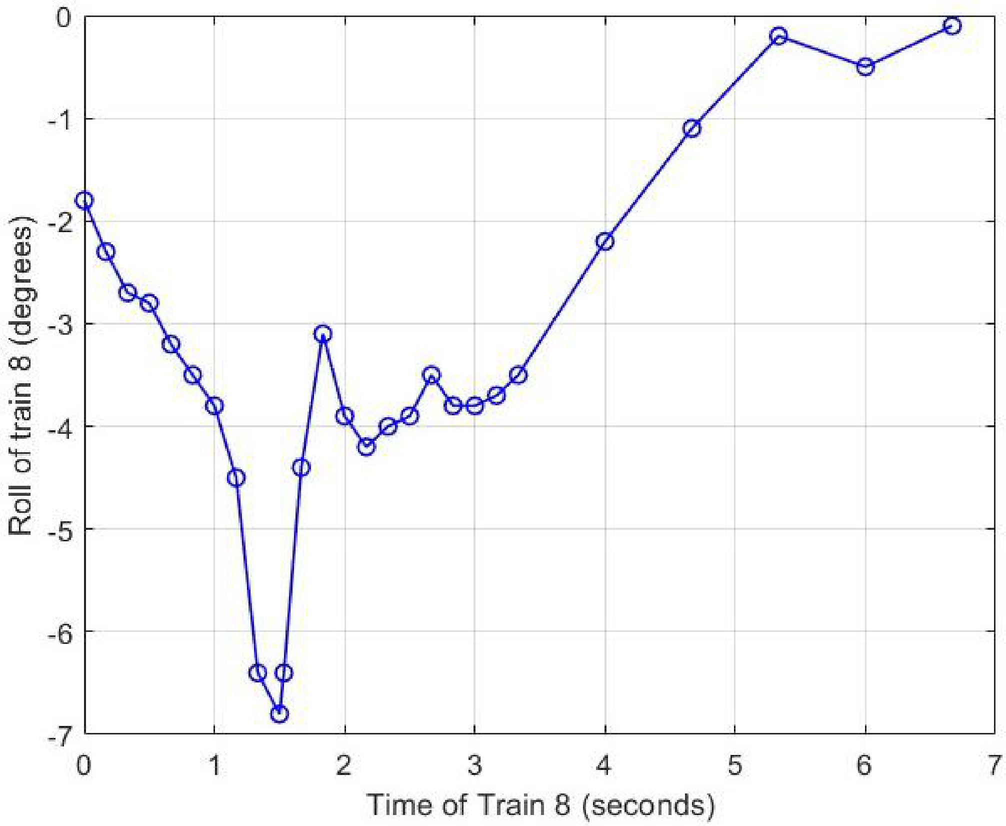

Figure 18. Measured roll angle of Amtrak train 8 (eastbound)

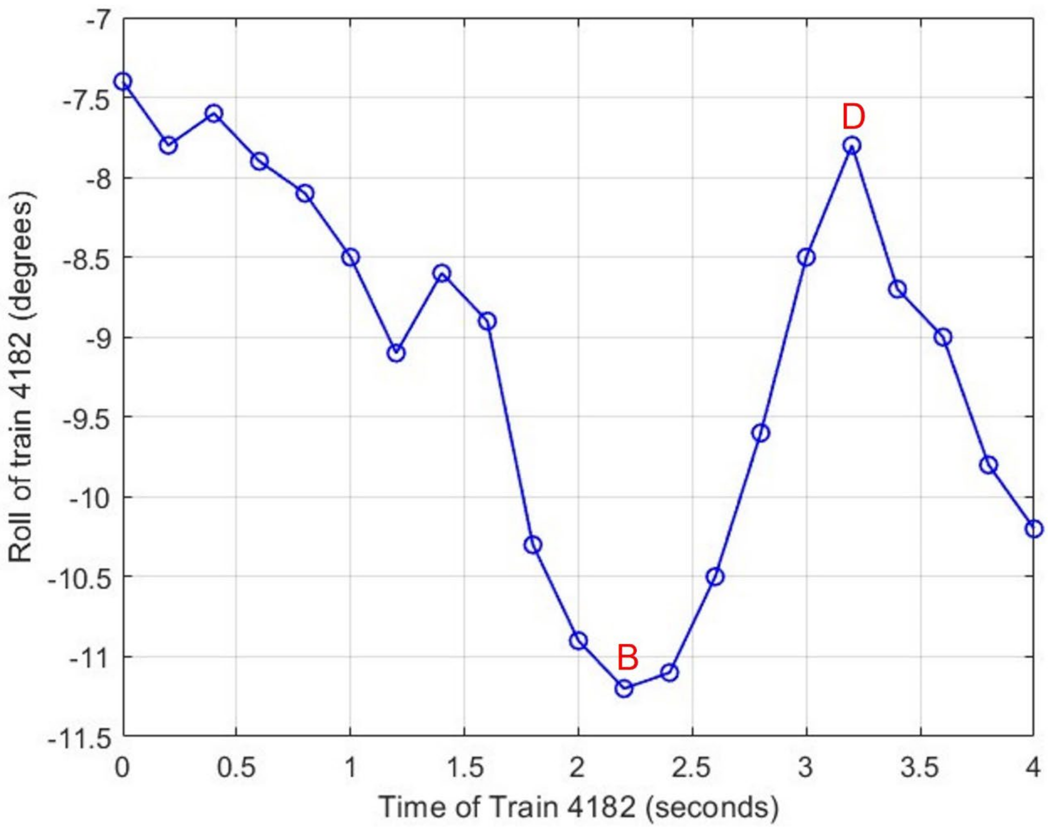

Figure 19. Measured roll angle of BNSF4182 train (eastbound)

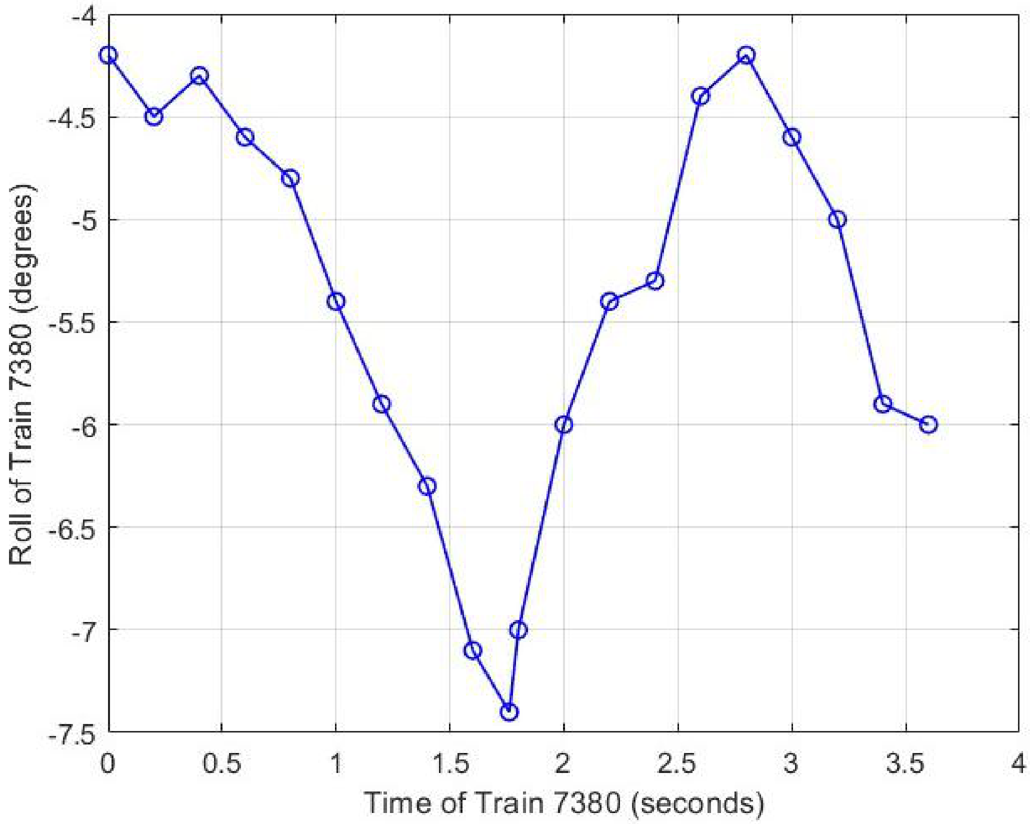

Figure 20. Measured roll angle of BNSF7380 train (eastbound)